

Search for the EDM of Ra-225

Matthew R. Dietrich

Physics Division

Argonne National Lab

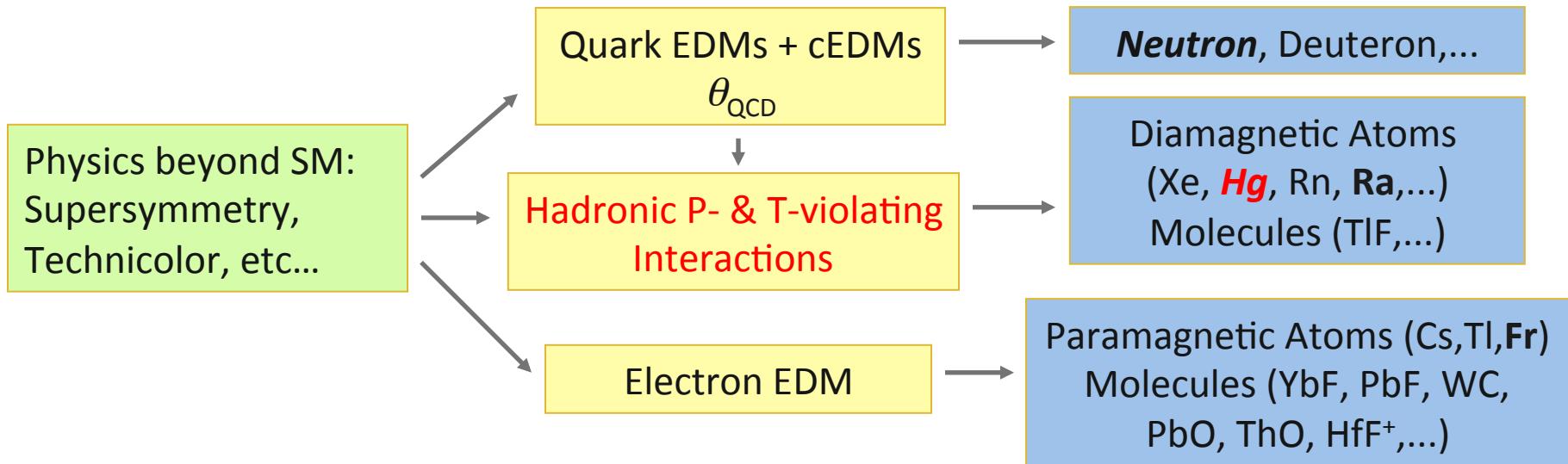
2012 Project X Physics Study

June 16, 2012

Supported by

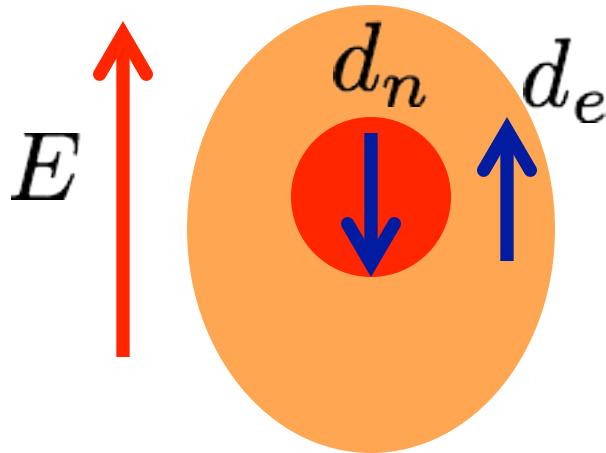
Department of Energy, Office of Nuclear Physics

EDM Sectors



Sector	Exp Limit (e-cm)	Method	Standard Model
Electron	1×10^{-27}	YbF molecules in a beam	10^{-38}
Neutron	3×10^{-26}	UCN in a bottle	10^{-31}
¹⁹⁹ Hg atom	3×10^{-29}	Hg atoms in a cell	10^{-33}

Schiff Moments and EDMs



Schiff Moment

$$\vec{S} = \frac{\langle e\vec{r}^2\vec{r} \rangle}{10} - \frac{\langle \vec{r}^2 \rangle \langle e\vec{r} \rangle}{6}$$

Schiff Theorem (1963):

- * Any permanent dipole moment of the nucleus is perfectly shielded by its electron cloud
- * True for point-like nuclei, non-relativistic electrons

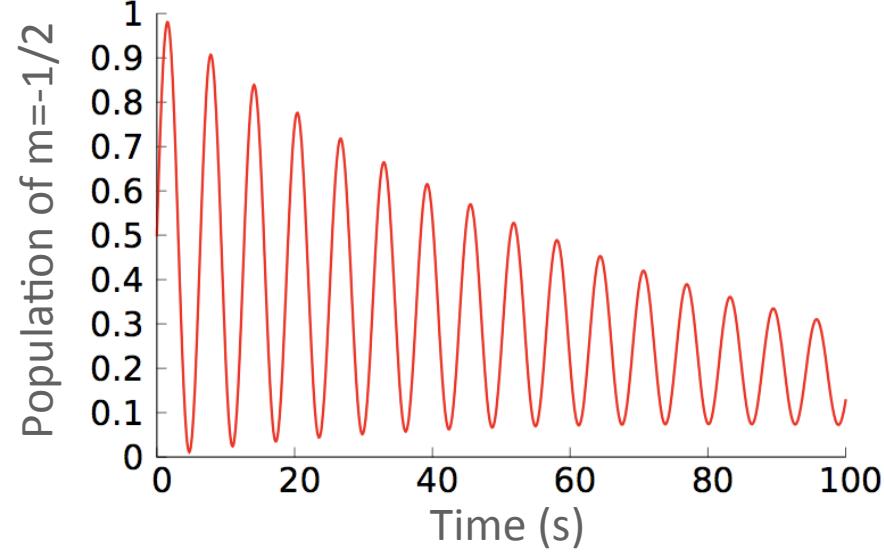
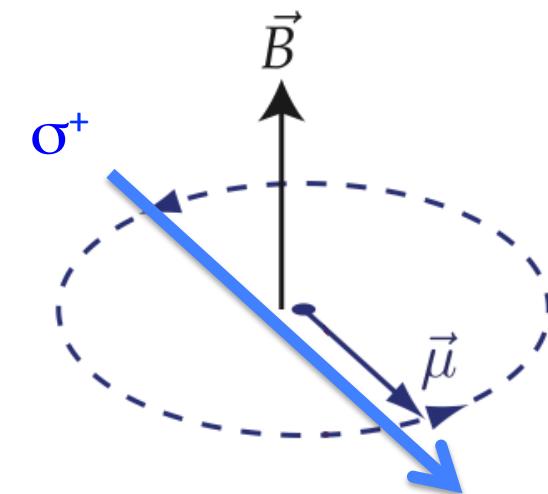
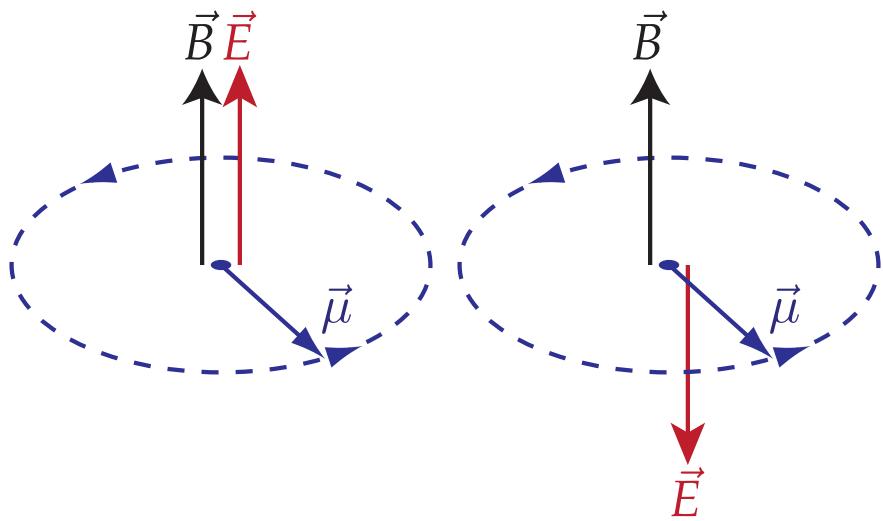
However, the “Schiff moment” is not shielded by this effect

- * Zero for point-like, spherical nuclei
- * Arises from deformations in the nucleus or its constituent nucleons
- * Very large in nuclei with both a quadrupole and octupole deformation

Look for heavy nuclei with large quadrupole and octupole deformations!

Measuring the EDM

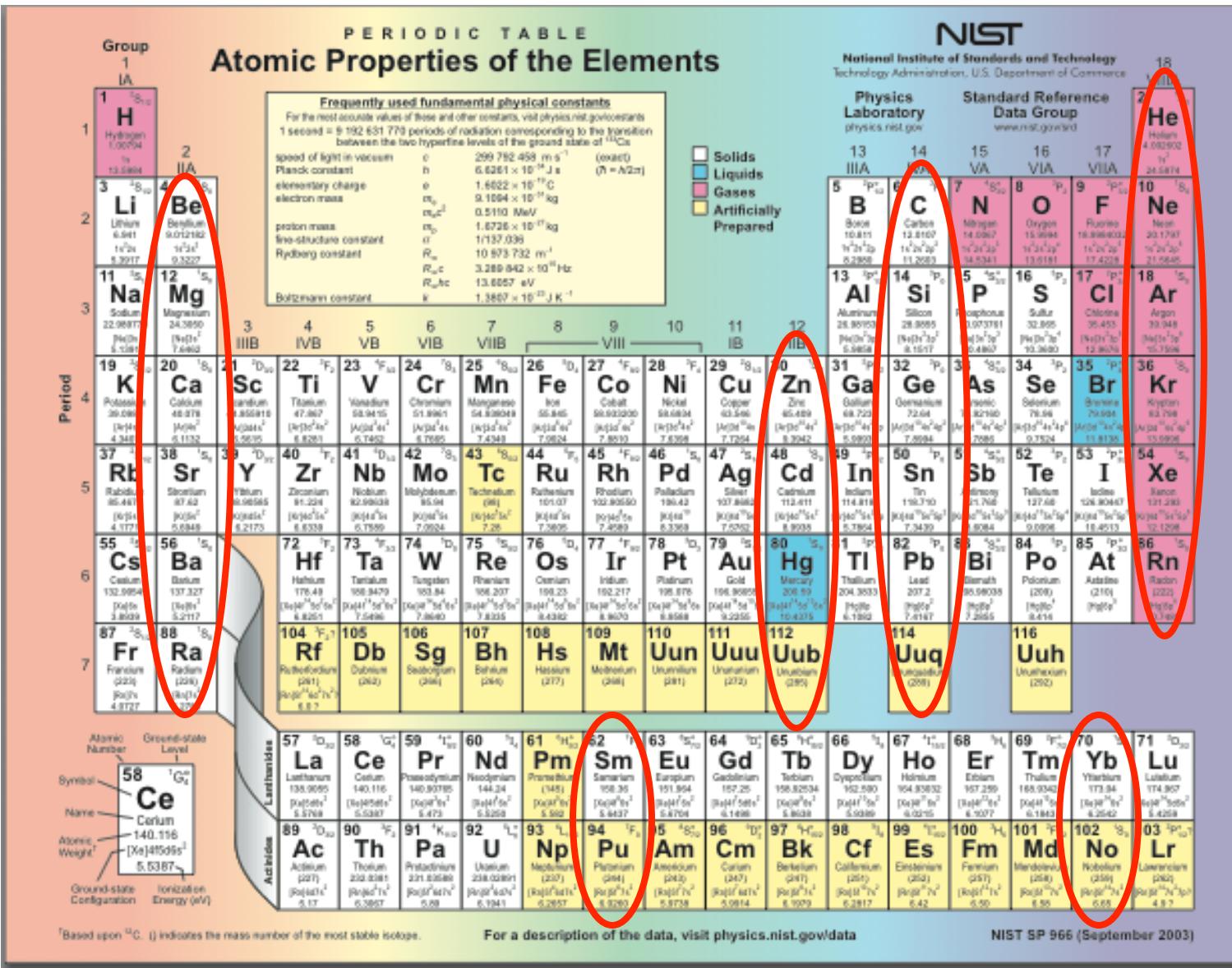
$$hv_{\pm} = \frac{\mu B \pm dE}{S}$$



Paramagnetic and Diamagnetic Atoms

Systematic	Paramagnetic (Electron EDM)	Diamagnetic (Nuclear EDM)
Electron Spin	$J=1/2, 1\dots$	$J=0$
Nuclear Spin	$I=0, 1/2, 1\dots$	$I=\textcolor{red}{1/2}, 1\dots$
Nuclear Mass	Large	Large
Nuclear Deformation	Small	Large
Examples	Fr, Cs...	Hg, Ra, Rn...

Candidate Nuclei



Candidate Nuclei

PERIODIC TABLE
Atomic Properties of the Elements

Frequently used fundamental physical constants
For the most accurate values of these and other constants, visit physics.nist.gov/constants
1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs
speed of light in vacuum c 299 792 458 m s⁻¹ (exact)
Planck constant \hbar 6.6261 × 10⁻³⁴ J s ($\hbar = h/2\pi$)
elementary charge e 1.602176 × 10⁻¹⁹ C
electron mass m_e 9.1094 × 10⁻³¹ kg
proton mass m_p 0.93826 MeV
fine-structure constant α 1/137.036
Rydberg constant R_∞ 10 973 732 m⁻¹
 $R_\infty c$ 3.289 842 × 10¹⁵ Hz
 $R_\infty hc$ 13.6557 eV
Boltzmann constant k 1.3807 × 10⁻²³ J K⁻¹

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

Group 1 IA		Periodic Table of the Elements																		Group 18 VIA	
1 H	2 He																				
Hydrogen	Helium																				
1.00794	4.002602																				
13.0894	24.5894																				
Group 2 IIA																					
3 Li	4 Be																				
Lithium	Beryllium																				
6.941	9.012																				
1.174	1.824																				
8.39917	9.3227																				
Group 11 VA																					
11 Na	12 Mg																				
Sodium	Magnesium																				
22.98770	24.3850																				
[Ne] 3s ¹	[Ne] 3s ²																				
Group 12 IIA																					
3 Be	4 Mg																				
Boron	Magnesium																				
11.971	24.3850																				
1.474	2.324																				
8.39917	9.3227																				
Group 13 IIIA																					
5 B	6 C																				
Boron	Carbon																				
11.971	12.011																				
1.474	2.011																				
8.39917	9.2858																				
Group 14 IVA																					
6 C	7 N																				
Carbon	Nitrogen																				
12.011	14.007																				
1.474	2.142																				
8.39917	11.2683																				
Group 15 VA																					
7 N	8 O																				
Nitrogen	Oxygen																				
14.007	15.999																				
1.474	2.142																				
8.39917	11.6181																				
Group 16 VIA																					
8 O	9 F																				
Oxygen	Fluorine																				
15.999	19.000																				
1.474	2.142																				
8.39917	17.4228																				
Group 17 VIIA																					
9 F	10 Ne																				
Fluorine	Neon																				
19.000	20.1790																				
[He] 2s ¹	[Ne] 2s ²																				
1.474	2.142																				
8.39917	9.2858																				
Group 18 VIA																					
2 He	3 Ne																				
Helium	Neon																				
4.002602	20.1790																				
[He]	[Ne]																				
1.474	2.142																				
8.39917	9.2858																				

Periodic Table Labels:

- Atomic Number
- Ground-state Level
- Symbol
- Name
- Atomic Weight[†]
- Ground-state Configuration
- Ionization Energy (eV)
- Actinides
- Ln = Lanthanides

[†]Based upon ^{12}C . (I) indicates the mass number of the most stable isotope.

For a description of the data, visit physics.nist.gov/data

NIST SP 966 (September 2003)

Candidate Nuclei

Best EDM limit from diamagnetic species
currently comes from Mercury-199:

$$|d(^{199}\text{Hg})| < 3.1 \times 10^{-29} \text{ e cm (95% C.L.)}$$

Griffith et al., PRL 102 101601 (2009)

The image shows a detailed periodic table of elements. A red circle highlights the element Mercury (Hg) in the second column of the fifth row. Another red circle highlights Radium (Ra) in the first column of the seventh row. A third red circle highlights Rhenium (Re) in the second column of the sixth row. The table includes atomic number, symbol, name, atomic weight, ground-state level, and ionization energy for each element. A legend at the bottom left identifies the color-coded regions: Lanthanides (orange), Actinides (light blue), and the rest of the elements (yellow).

5	Radium 88.4478 [Kr]4d ² 4.9173	Samarium 157.62 [Eu] ²⁺ 5.9348	Yttrium 88.9885 [Eu] ²⁺ 6.2173	Zirconium 91.221 [Eu] ²⁺ 6.6339	Hafnium 178.94 [Eu] ²⁺ 7.0524	Molybdenum 95.94 [Eu] ²⁺ 7.26	Tantalum 101.07 [Eu] ²⁺ 7.4593	Ruthenium 101.07 [Eu] ²⁺ 7.6369	Rhodium 102.9050 [Eu] ²⁺ 7.8369	Palladium 106.42 [Eu] ²⁺ 8.3369	Silver 107.862 [Eu] ²⁺ 7.9592	Chromium 124.611 [Eu] ²⁺ 8.9358	Iridium 114.418 [Eu] ²⁺ 8.7854	Tin 118.710 [Eu] ²⁺ 7.3439	Antimony 121.76 [Eu] ²⁺ 8.8084	Tellurium 127.66 [Eu] ²⁺ 8.0908	Iodine 126.9040 [Eu] ²⁺ 11.4513	Xenon 131.200 [Eu] ²⁺ 12.08
6	55 ^{1S_{1/2}} Cs Csium 132.98545 [Ba] ²⁺ 2.3608	56 ^{1S_{1/2}} Ba Barium 137.327 [Ba] ²⁺ 1.8211	72 ^{1T₁} Hf Hafnium 178.49 [Ta] ²⁺ 6.8201	73 ^{3P₀} Ta Tantalum 186.8479 [W] ²⁺ 7.0335	74 ^{3D₂} W Tungsten 183.84 [Re] ²⁺ 7.3335	75 ^{3P₂} Re Rhenium 196.207 [Os] ²⁺ 8.4330	76 ^{3D₄} Os Osmium 199.23 [Ir] ²⁺ 8.8330	77 ^{3P₁} Ir Iridium 192.217 [Pt] ²⁺ 8.8330	78 ^{3D₅} Pt Platinum 195.871 [Au] ²⁺ 10.4330	79 ^{5S_{1/2}} Au Gold 196.9695 [Hg] ²⁺ 10.4330	80 ^{5P_{1/2}} Hg Mercury 206.93 [Tl] ²⁺ 204.3633	81 ^{3P_{1/2}} Tl Thallium 207.2 [Pb] ²⁺ 7.3439	82 ^{3P₁} Pb Lead 207.2 [Bi] ²⁺ 7.3439	83 ^{3P₀} Bi Bismuth 208.59038 [Po] ²⁺ 8.4114	84 ^{3P₂} Po Polonium (208) [At] ²⁺ 8.4114	85 ^{3P₂} At Astatine (210) [Rn] ²⁺ 8.4114	86 ^{1S_{1/2}} Rn Radon (222) [He] ²⁺ 8.4114	
7	87 ^{1S_{1/2}} Fr Francium 222.0209 [Ra] ²⁺ 4.8727	88 ^{1S_{1/2}} Ra Radium (226) [Ra] ²⁺ 5.2794	104 ^{1F₅} Rf Rutherfordium (261) [Rf] ²⁺ 6.87	105 ^{1F₄} Db Dubnium (262)	106 ^{1F₅} Sg Seaborgium (263)	107 ^{1F₇} Bh Bohrium (264)	108 ^{1F₆} Hs Hassium (265)	109 ^{1F₇} Mt Meitnerium (266)	110 ^{1F₈} Uun Ununnilium (267)	111 ^{1F₉} Uub Ununbium (268)	114 ^{1F₁₀} Uuq Ununquadium (269)	116 ^{1F₁₁} Uuh Ununhexium (269)						
			57 ^{1D₂} La Lanthanum 138.9095 [Ce] ²⁺ 5.5380	58 ^{1G₄} Ce Cerium 140.116 [Ce] ²⁺ 5.5380	59 ^{1I₆} Pr Praseodymium 140.92395 [Pr] ²⁺ 5.4733	60 ^{1D₃} Nd Neodymium 144.24 [Nd] ²⁺ 5.5862	61 ^{1G₇} Pm Promethium (145) [Pm] ²⁺ 5.6437	62 ^{1F₅} Sm Samarium 158.95 [Eu] ²⁺ 5.6705	63 ^{1G₈} Eu Europium 151.954 [Eu] ²⁺ 5.6705	64 ^{1D₃} Gd Gadolinium 157.25 [Gd] ²⁺ 5.6705	65 ^{1H₉} Tb Terbium 158.82534 [Tb] ²⁺ 5.6705	66 ^{1I₈} Dy Dysprosium 162.590 [Dy] ²⁺ 5.6705	67 ^{1I₁₂} Ho Holmium 164.93632 [Ho] ²⁺ 5.6705	68 ^{1H₉} Er Erbium 167.259 [Er] ²⁺ 5.6705	69 ^{1P_{1/2}} Tm Thulium 168.93421 [Tm] ²⁺ 5.6705	70 ^{1S_{1/2}} Yb Ytterbium 173.84 [Yb] ²⁺ 5.6705	71 ^{1D₂} Lu Lutetium 174.957 [Lu] ²⁺ 5.6705	
			89 ^{1D₂} Ac Actinium (227) [Th] ²⁺ 5.17	90 ^{1P₁} Th Thorium 232.0311 [Pa] ²⁺ 5.2853	91 ^{1K_{1/2}} Pa Protactinium 231.0318 [U] ²⁺ 5.1941	92 ^{1L_{1/2}} U Uranium 238.0281 [Np] ²⁺ 5.1941	93 ^{1L_{1/2}} Np Neptunium (237) [Pu] ²⁺ 5.2853	94 ^{1F₅} Pu Plutonium (239) [Am] ²⁺ 5.9718	95 ^{1B_{1/2}} Am Americium (241) [Cm] ²⁺ 5.9814	96 ^{1D₁} Cm Curium (247) [Bk] ²⁺ 5.9814	97 ^{1H₉} Bk Berkelium (247) [Cf] ²⁺ 5.9814	98 ^{1I₈} Cf Californium (251) [Es] ²⁺ 6.2812	99 ^{1P_{1/2}} Es Einsteinium (252) [Fm] ²⁺ 6.42	100 ^{1P_{1/2}} Fm Fermium (257) [Md] ²⁺ 6.55	101 ^{1F₅} Md Mendelevium (258) [No] ²⁺ 6.65	102 ^{1S_{1/2}} No Nobelium (259) [Lr] ²⁺ 6.72	103 ^{1P_{1/2}} Lr Lawrencium (262) [Rf] ²⁺ 6.72	

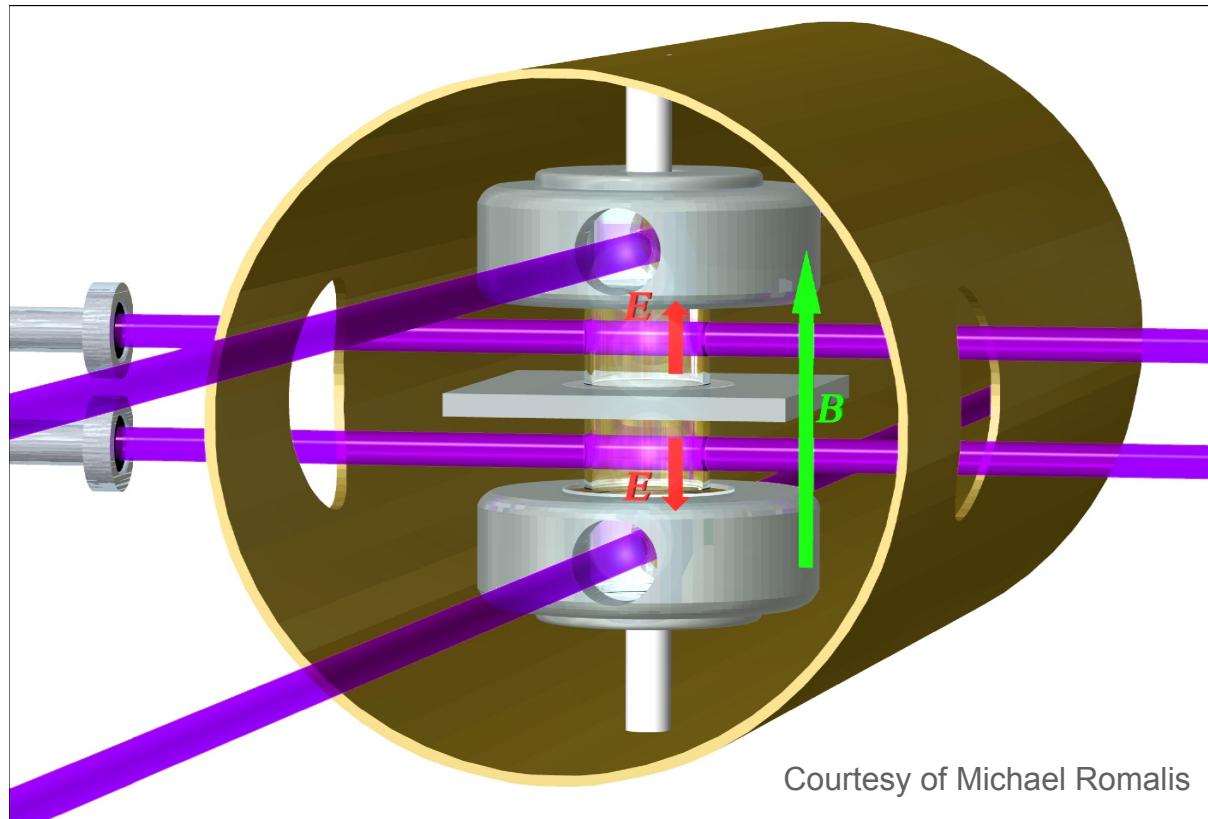
^aBased upon ¹²C. (i) indicates the mass number of the most stable isotope.

For a description of the data, visit physics.nist.gov/data

NIST SP 966 (September 2003)

Hg-199 in Seattle, Washington

Stable, high Z, groundstate 1S_0 , $I = \frac{1}{2}$, high vapor pressure

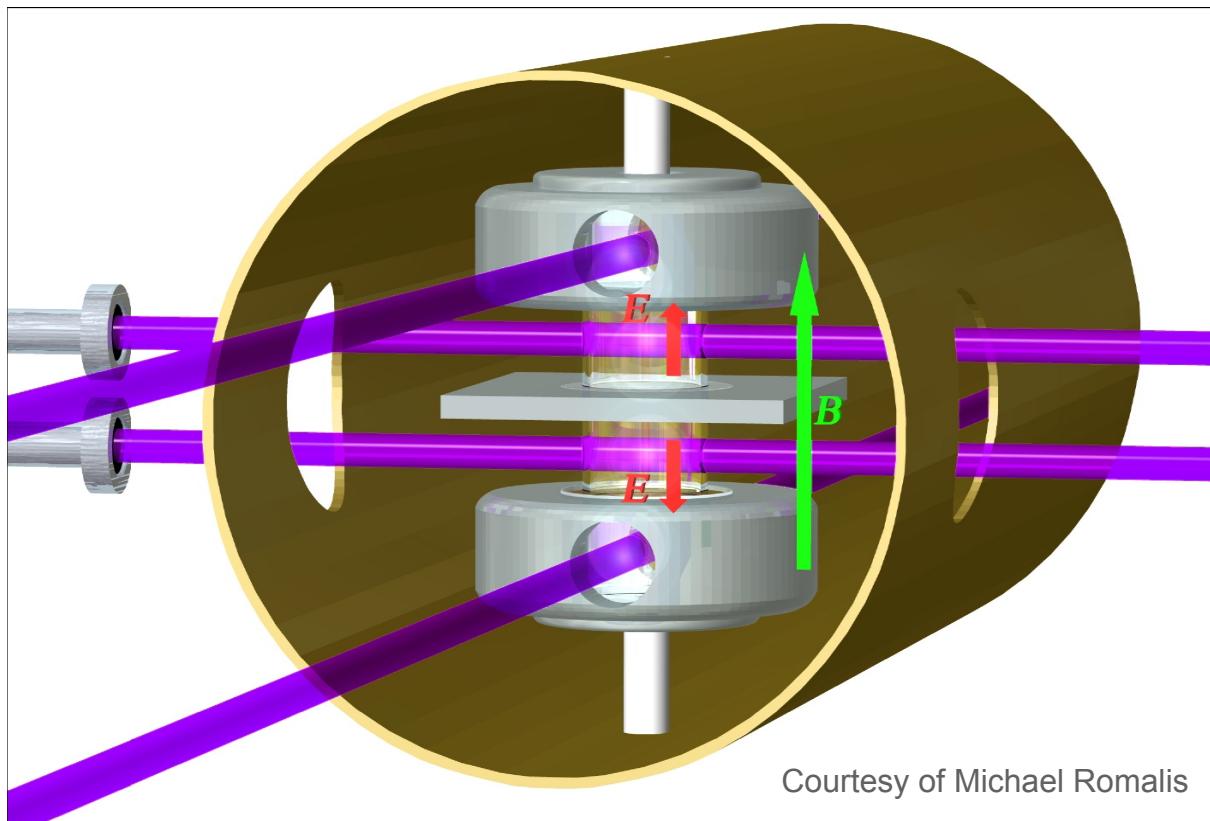


Hg-199 In Glass Cell:

- * Maximum voltage limited by dielectric breakdown. 10 kV/cm
- * Systematically limited by currents from leakage across glass

Hg-199 in Seattle, Washington

Stable, high Z, groundstate 1S_0 , $I = \frac{1}{2}$, high vapor pressure



$$B = 10\text{mG}$$

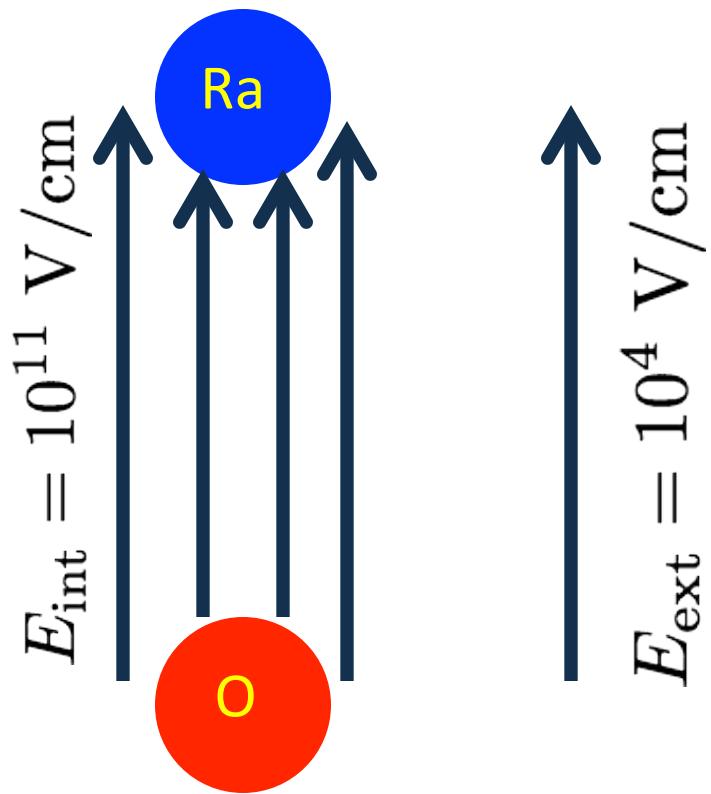
$$E = 10\text{kV/cm}$$

$$f_+ = \frac{2\mu B + 2dE}{h} \approx 15 \text{ Hz}$$

$$f_- = \frac{2\mu B - 2dE}{h} \approx 15 \text{ Hz}$$

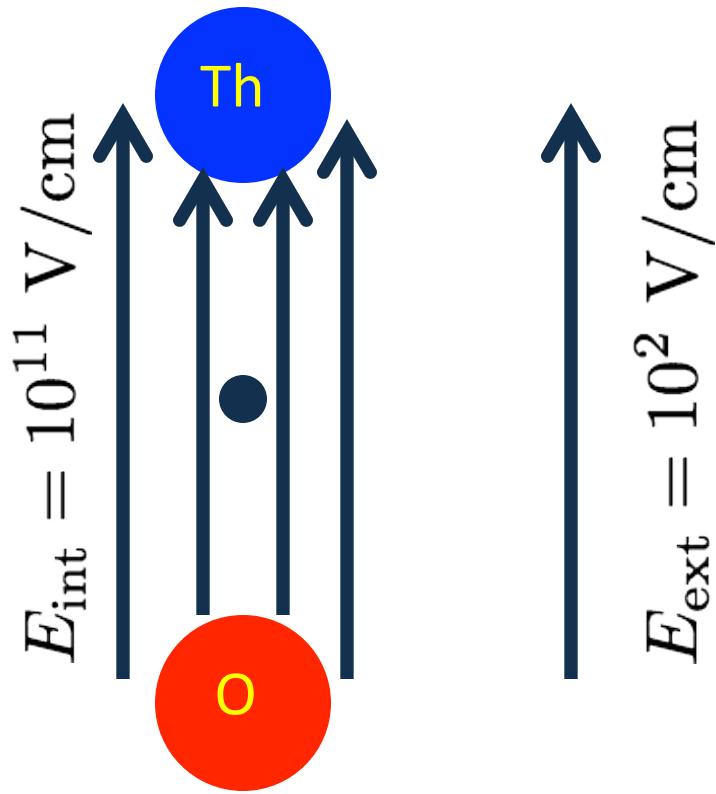
$$|f_+ - f_-| < 0.1 \text{ nHz}$$

Molecular EDM Searches



- Use a molecule to enhance the EDM signal
- Choose one highly electronegative, one electropositive. Large polarizability.
- Can be completely polarized using a weak field
- Difficult to access and control with lasers

Molecular EDM Searches



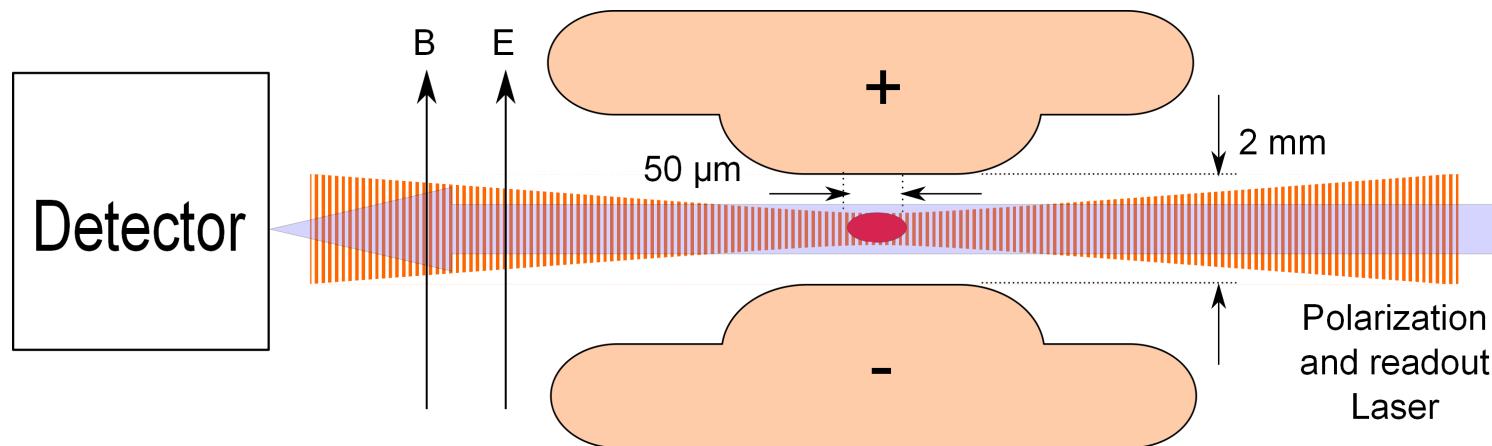
- Radicals can survive without reacting for a long time in vacuum
- Now the free electron dominates the Larmor precession
- Radicals are also easier to control with lasers
- YbF sets the best current limit on eEDM (Hudson et al., Nature 473, 493 (2011))

Glass-less measurement: Bottle of light

Atoms confined in optical dipole trap

- * Maximum voltage now set by breakdown of vacuum, 300 kV/cm
- * Leakage current less important
- * New Systematic: Stark Interference
- * Requires atom temperature < 1 mK
- * Low temperature and precision control allow us to use a small number of atoms

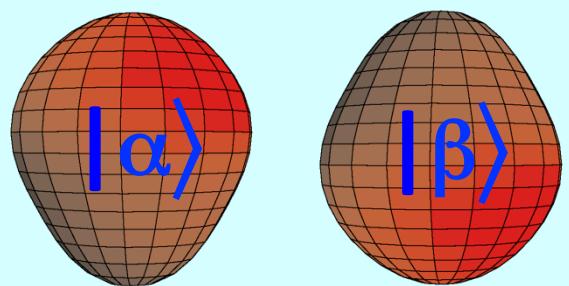
M. V. Romalis and E. N. Fortson PRA 59, 4547 (1999)



Why Radium?

- Shielding in Diamagnetic Atoms – Schiff (1963)
- Closely spaced parity doublet – Haxton & Henley (1983)
- Large intrinsic Schiff moment due to octupole deformation – Auerbach, Flambaum & Spevak (1996)
- Relativistic atomic structure (^{225}Ra / $^{199}\text{Hg} \sim 3$)
– Dzuba, Flambaum, Ginges, Kozlov (2002)

Parity doublet



$$\Psi^- = (|\alpha\rangle - |\beta\rangle)/\sqrt{2}$$
$$\Psi^+ = (|\alpha\rangle + |\beta\rangle)/\sqrt{2}$$

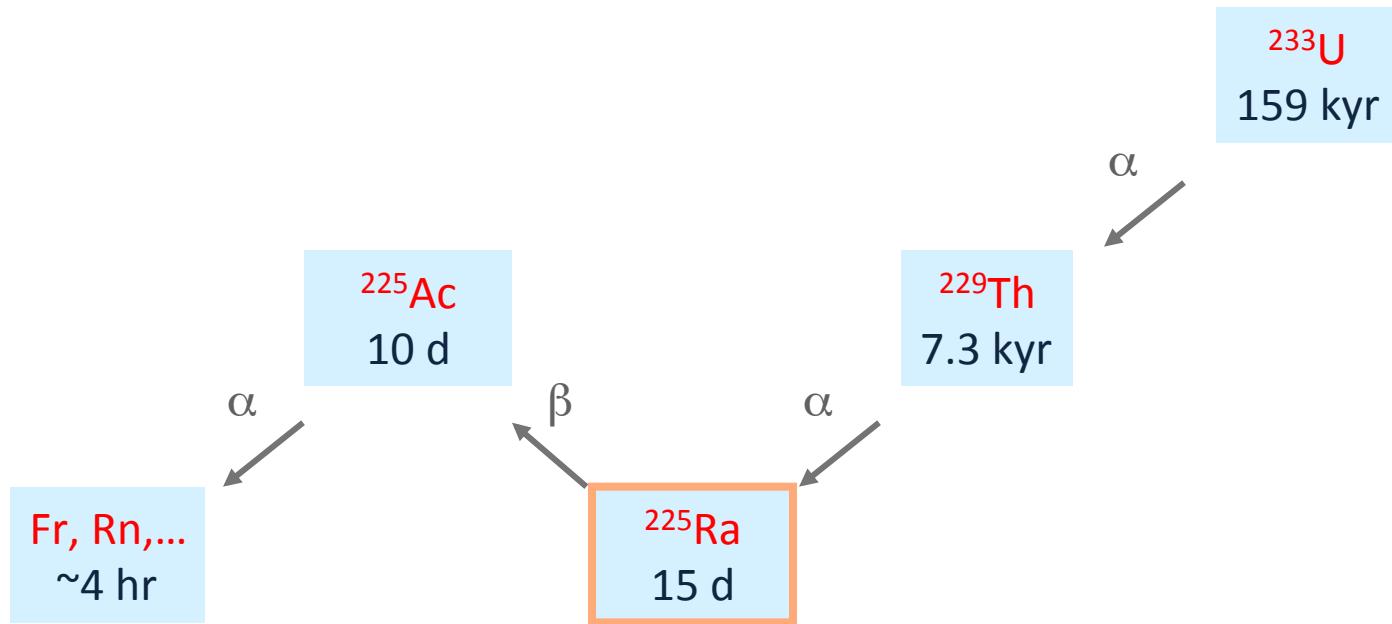
$$d \propto \sum_{i \neq 0} \frac{\langle \psi_o | \hat{S}_z | \psi_i \rangle \langle \psi_i | \hat{H}_{\text{PT}} | \psi_0 \rangle}{E_0 - E_i} + c.c.$$

Enhancement Factor: EDM (^{225}Ra) / EDM (^{199}Hg)

Skyrme Model	Isoscalar	Isovector	Isotensor
SIII	300	4000	700
SkM*	300	2000	500
SLy4	700	8000	1000

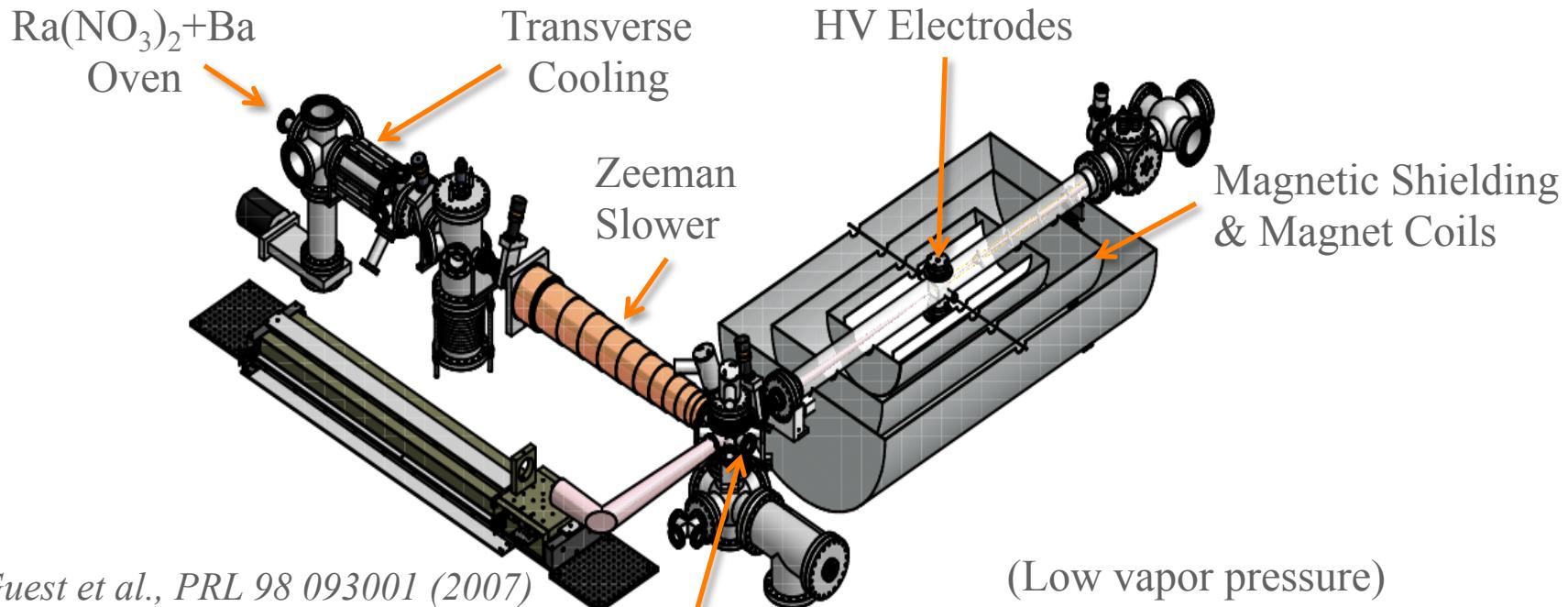
Schiff moment of ^{225}Ra , Dobaczewski, Engel (2005)
Schiff moment of ^{199}Hg , Ban, Dobaczewski, Engel, Shukla (2010)

Radium Source

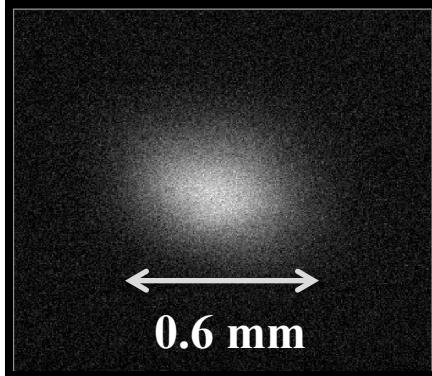


- Up to 30 mCi (750 ng) ^{225}Ra sources from:
National Isotope Development Center (Oak Ridge, TN)
- Test source: 1 μCi (1 μg) ^{226}Ra
- Integrated Atomic Beam Flux $\sim 10^8/\text{s}$

Radium



J. R. Guest et al., PRL 98 093001 (2007)

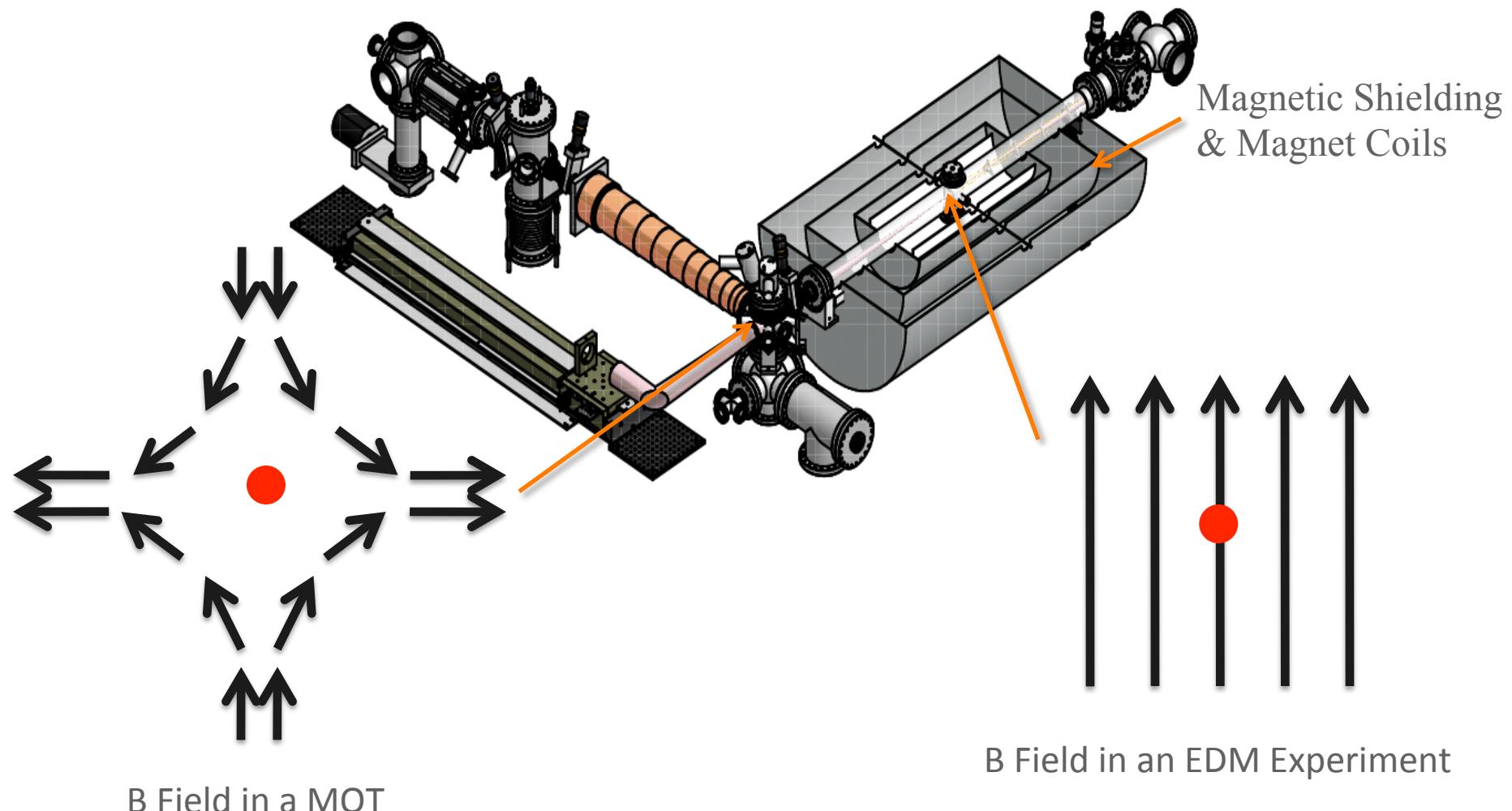


²²⁶Ra MOT
20,000 atoms

For EDM:
Ra-225
 $I = 1/2, J = 0$
 $t_{1/2} = 15$ days

For Testing:
Ra-226
 $I = 0, J = 0$
 $t_{1/2} = 1600$ yrs

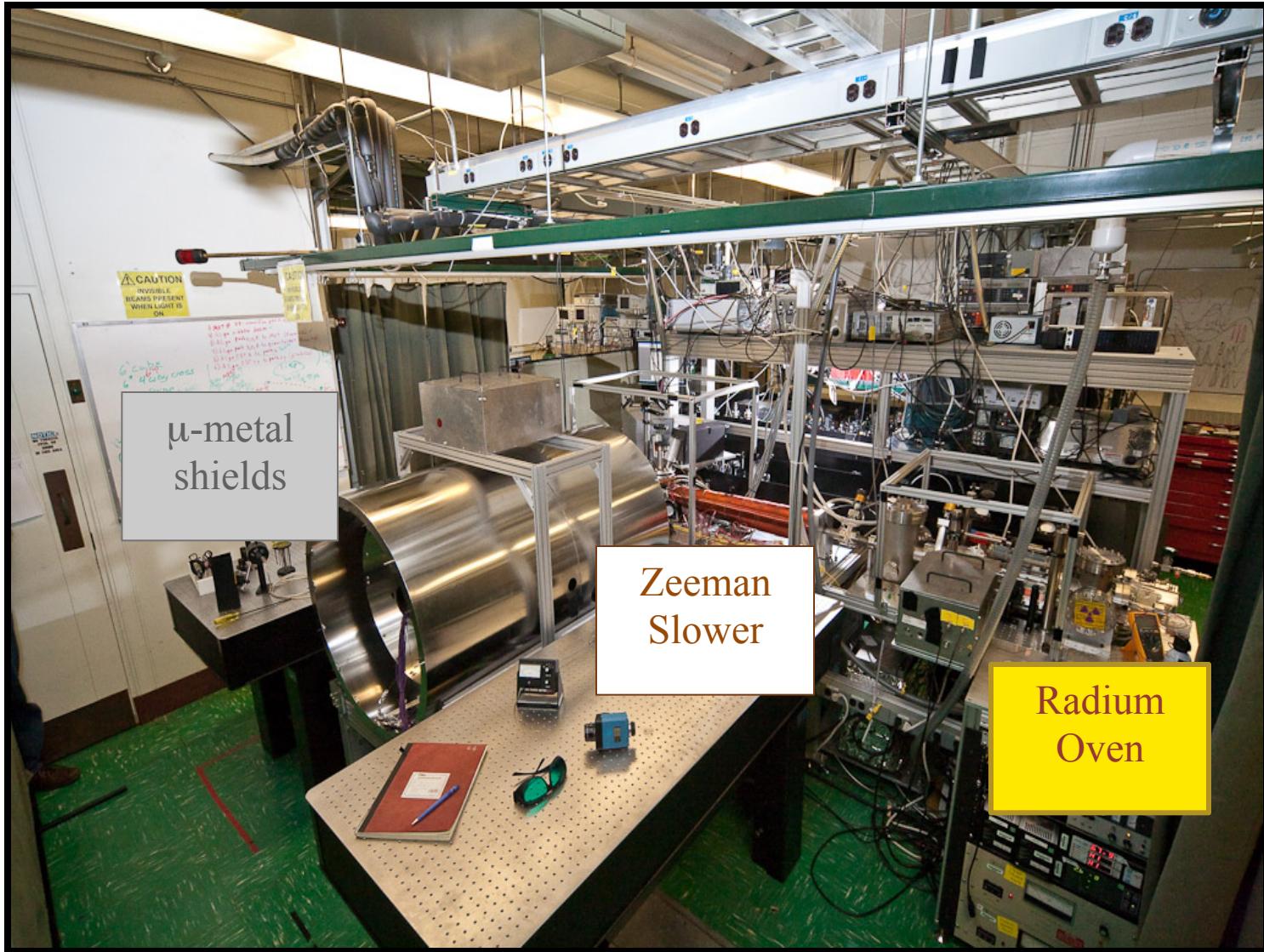
MOTs and EDM Measurements



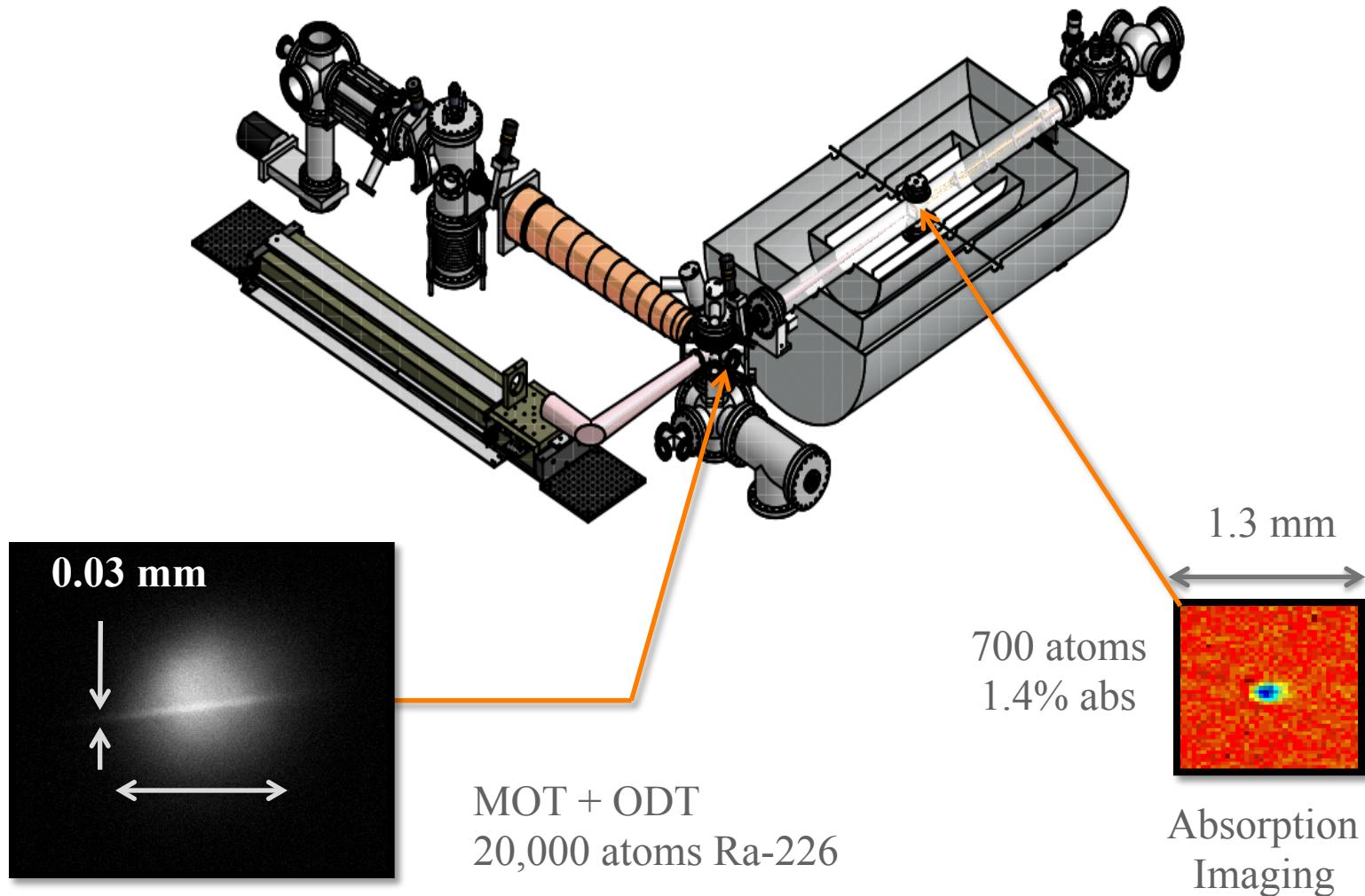
B Field in a MOT

B Field in an EDM Experiment

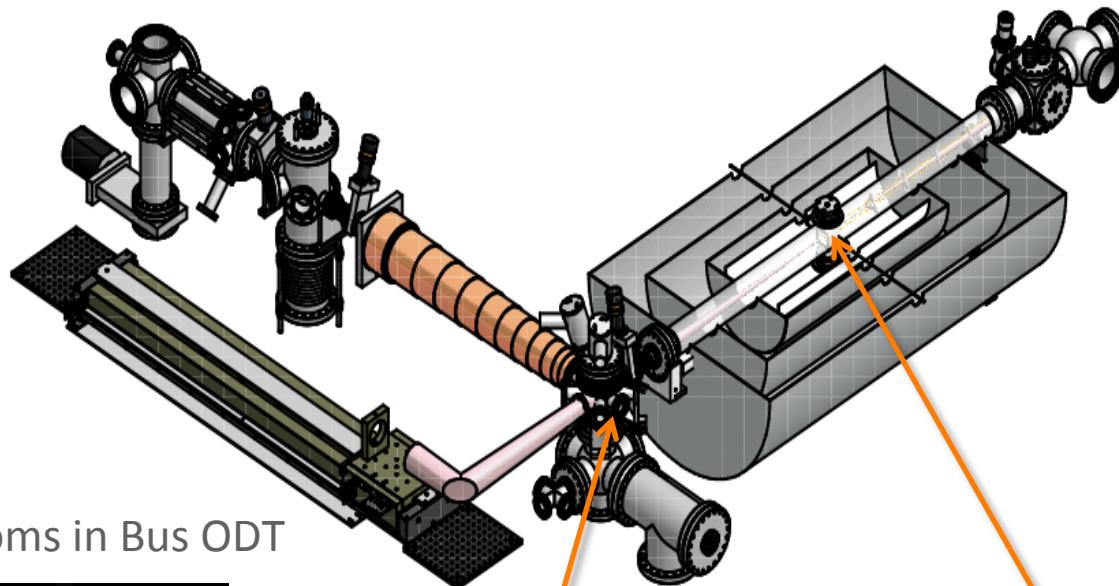
Apparatus



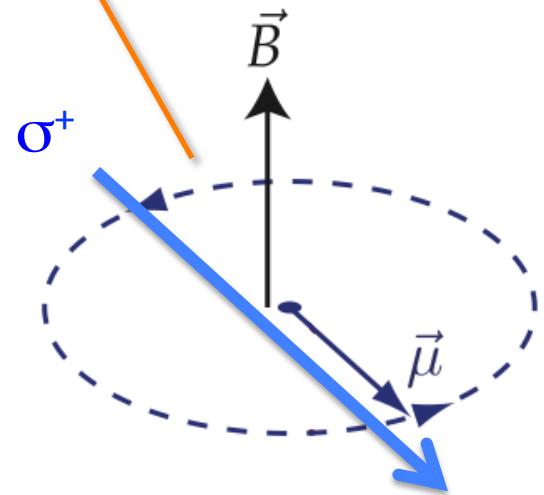
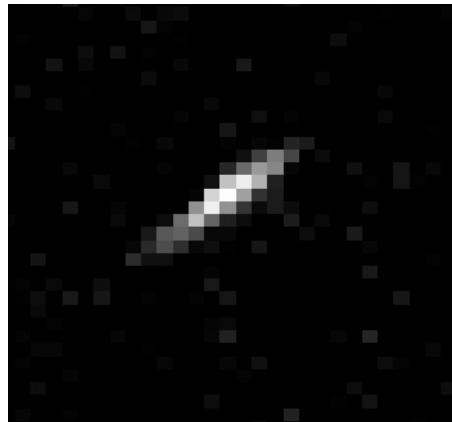
Ra-225 Status



Ra-225 Status



~70 Ra-225 Atoms in Bus ODT



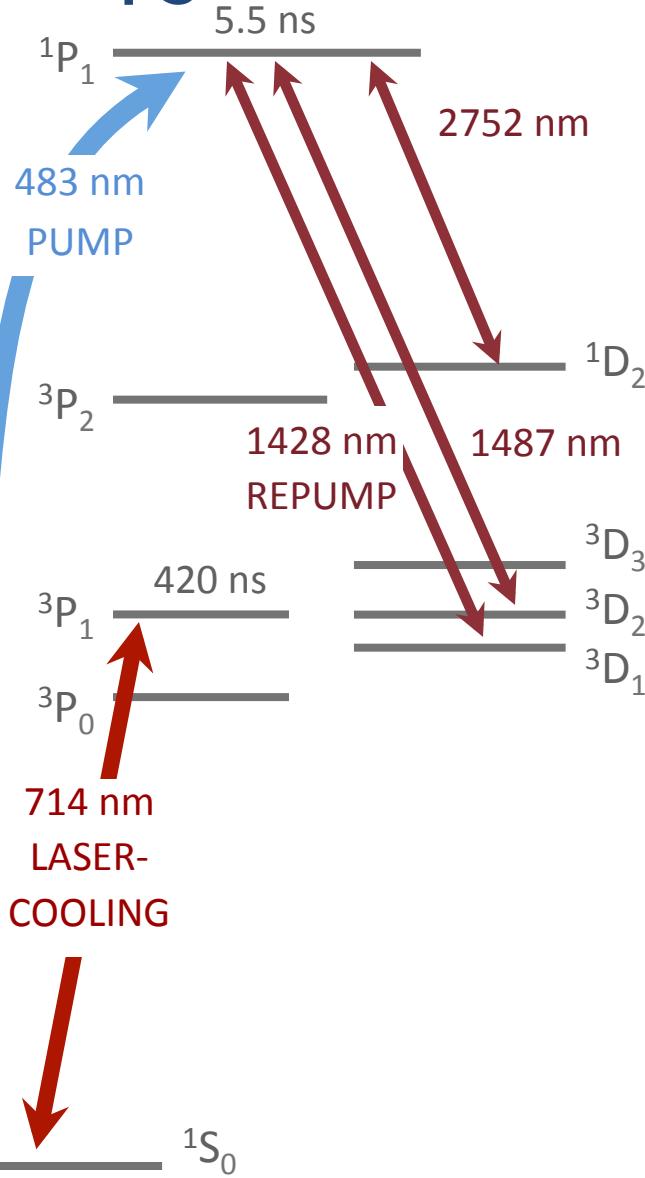
Statistics

$$\sigma_d^{\text{stat}} \geq \frac{\hbar}{2E\sqrt{\varepsilon N \tau T}}$$

parameter	present status w/ Ra-226	near term goal for Ra-225	comments
E , electric field (kV/cm)	100	100	complete HV system assembly
ε , efficiency	~0.1	0.1	optimize detection
N , # of atoms	10^3	10^3	vacuum upgrade
τ , storage time (s)	14	100	vacuum upgrade Optical Stability
T , integration time (days)	N/A	10	

initial goal of $3 \times 10^{-26} e \text{ cm (1}\sigma\text{)}$ is competitive with the best limits from Hg-199

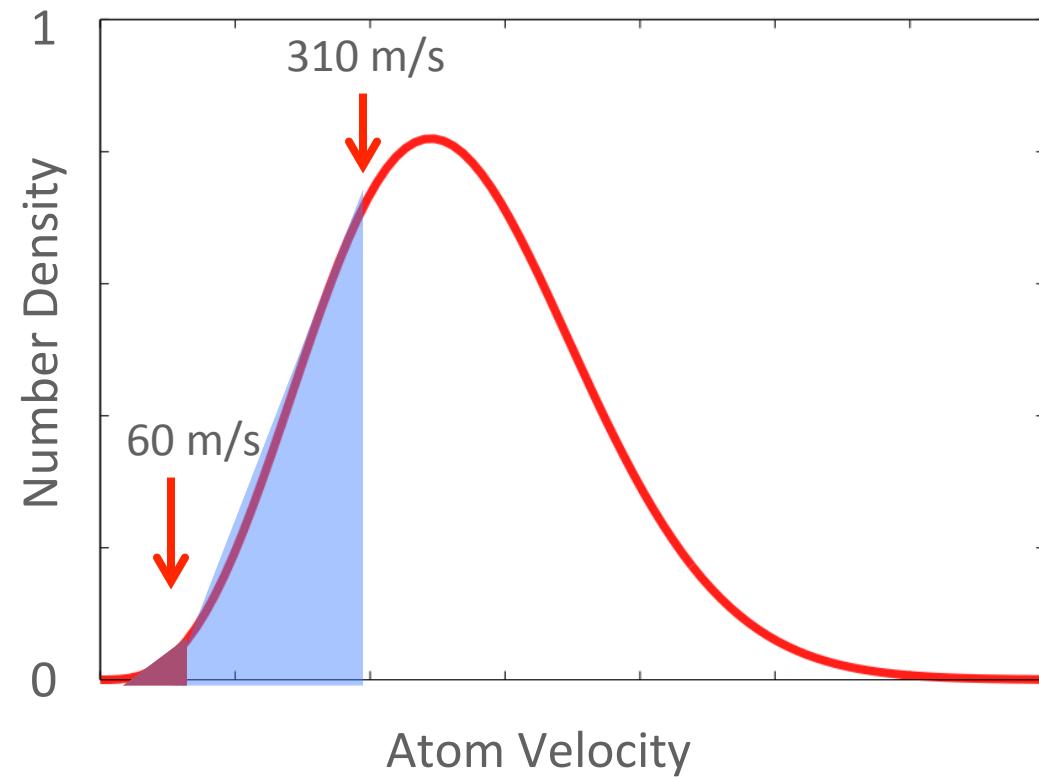
Blue Upgrade



2012 Project X Physics Study

$$\sigma_d^{\text{stat}} \geq \frac{\hbar}{2E\sqrt{8N\tau T}}$$

x30 – x100 Atom Capture Efficiency



Project X

I.C. Gomes, J. Nolen et al.
Project X workshop, July 2012

Protons on thorium target: $1 \text{ mA} \times 1000 \text{ MeV} = 1 \text{ MW}$

Predicted yields of some important isotopes:

Radon: $^{211}\text{Rn} > 10^{13}$ $^{223}\text{Rn} \sim 10^{11} / \text{s}$

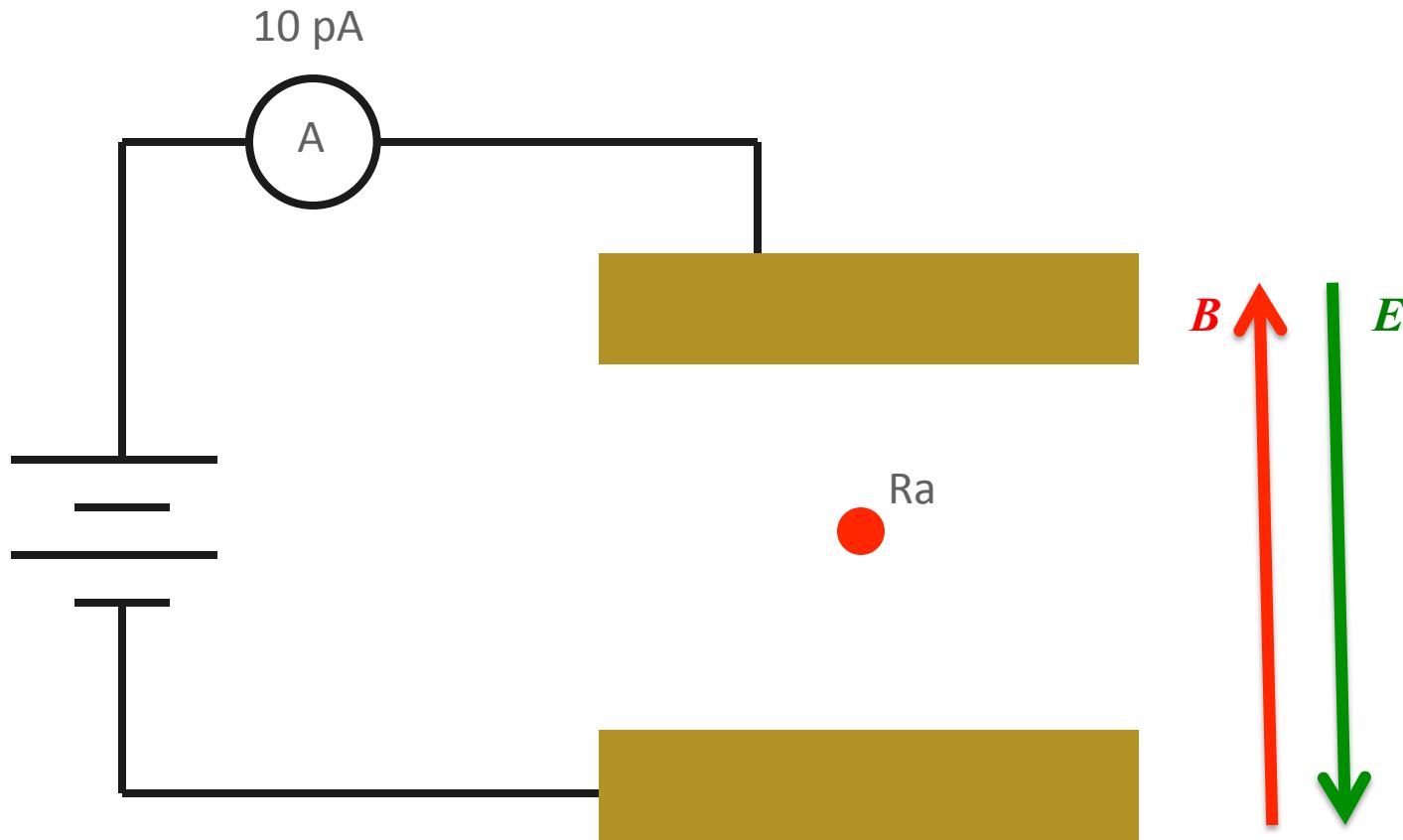
Francium: $^{213}\text{Fr} > 10^{13}$ $^{221}\text{Fr} > 10^{14}$ $^{223}\text{Fr} > 10^{12} / \text{s}$

Radium: $^{223}\text{Ra} > 10^{13}$ $^{225}\text{Ra} > 10^{13} / \text{s}$

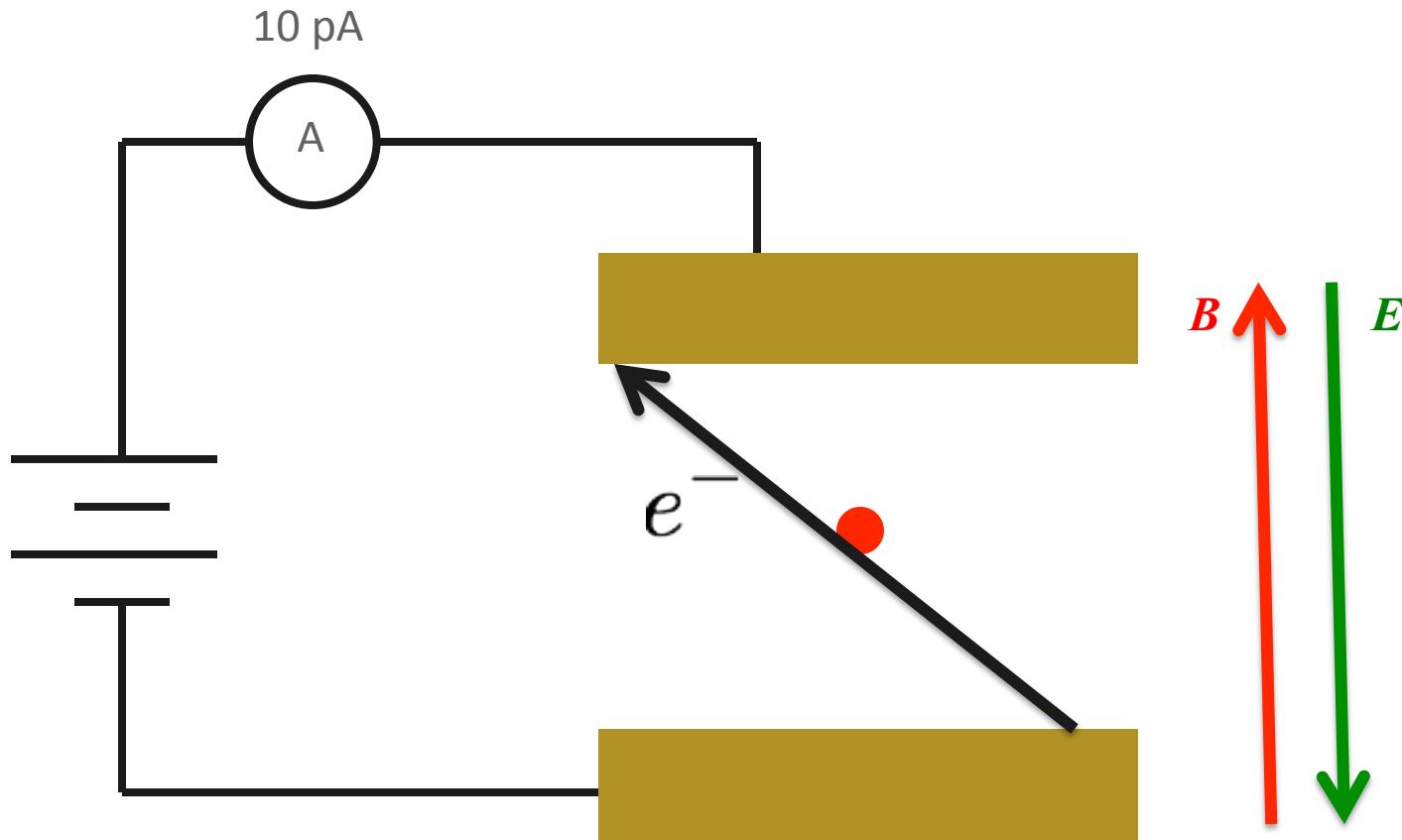
Actinium: $^{225-229}\text{Ac} > 10^{14} / \text{s}$

Compare $10^8 / \text{s}$ Today

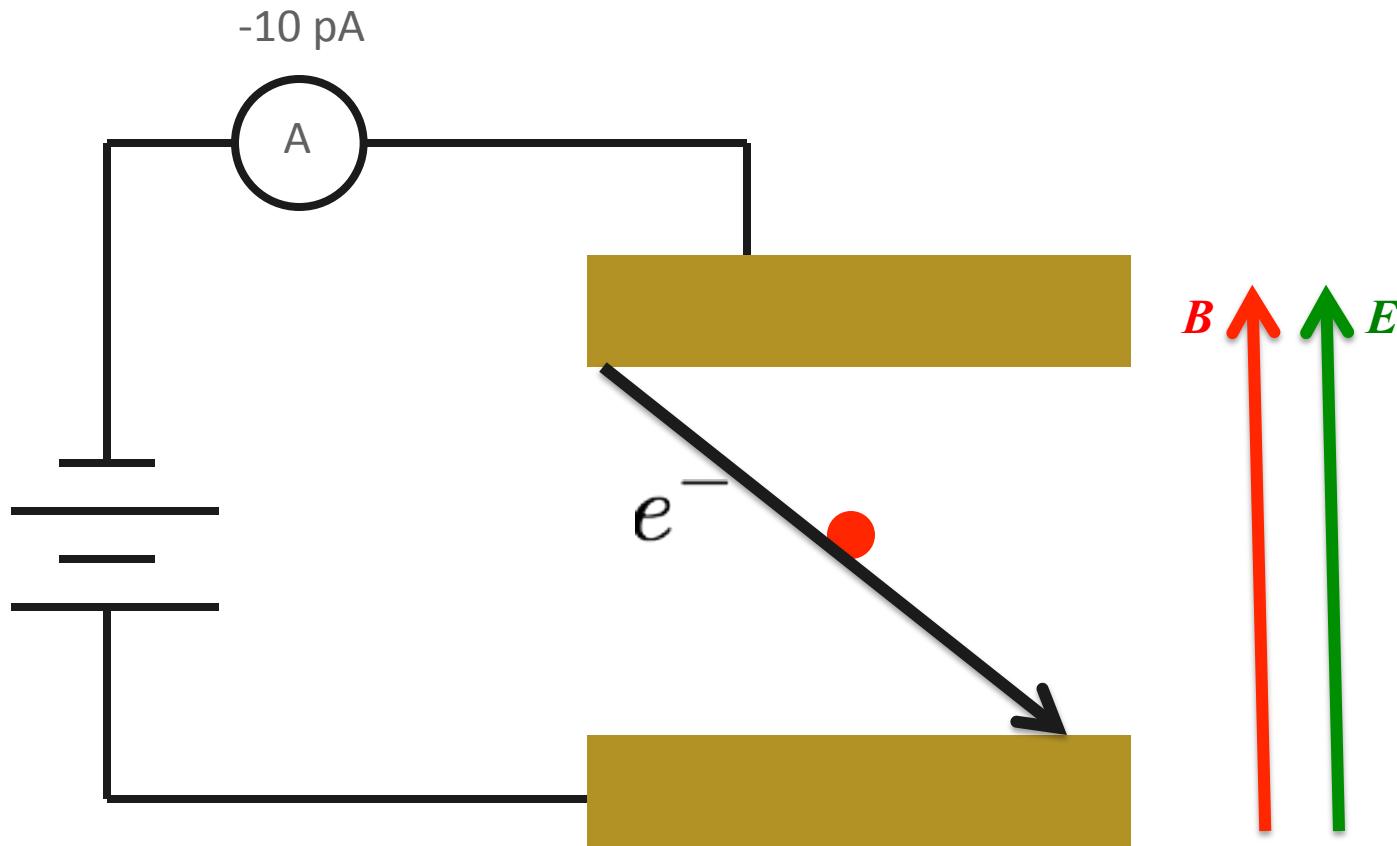
Leakage Current Systematic



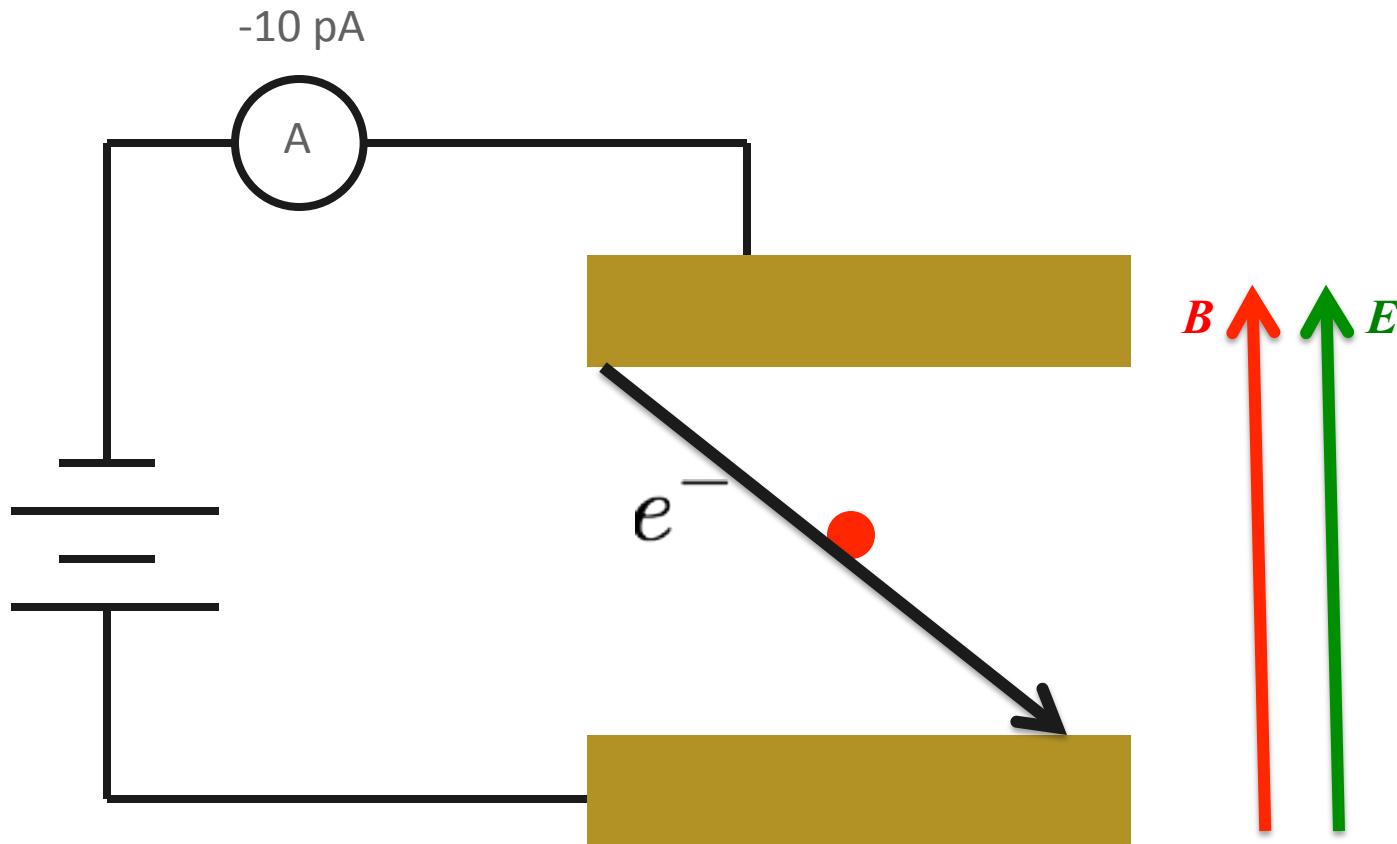
Leakage Current Systematic



Leakage Current Systematic

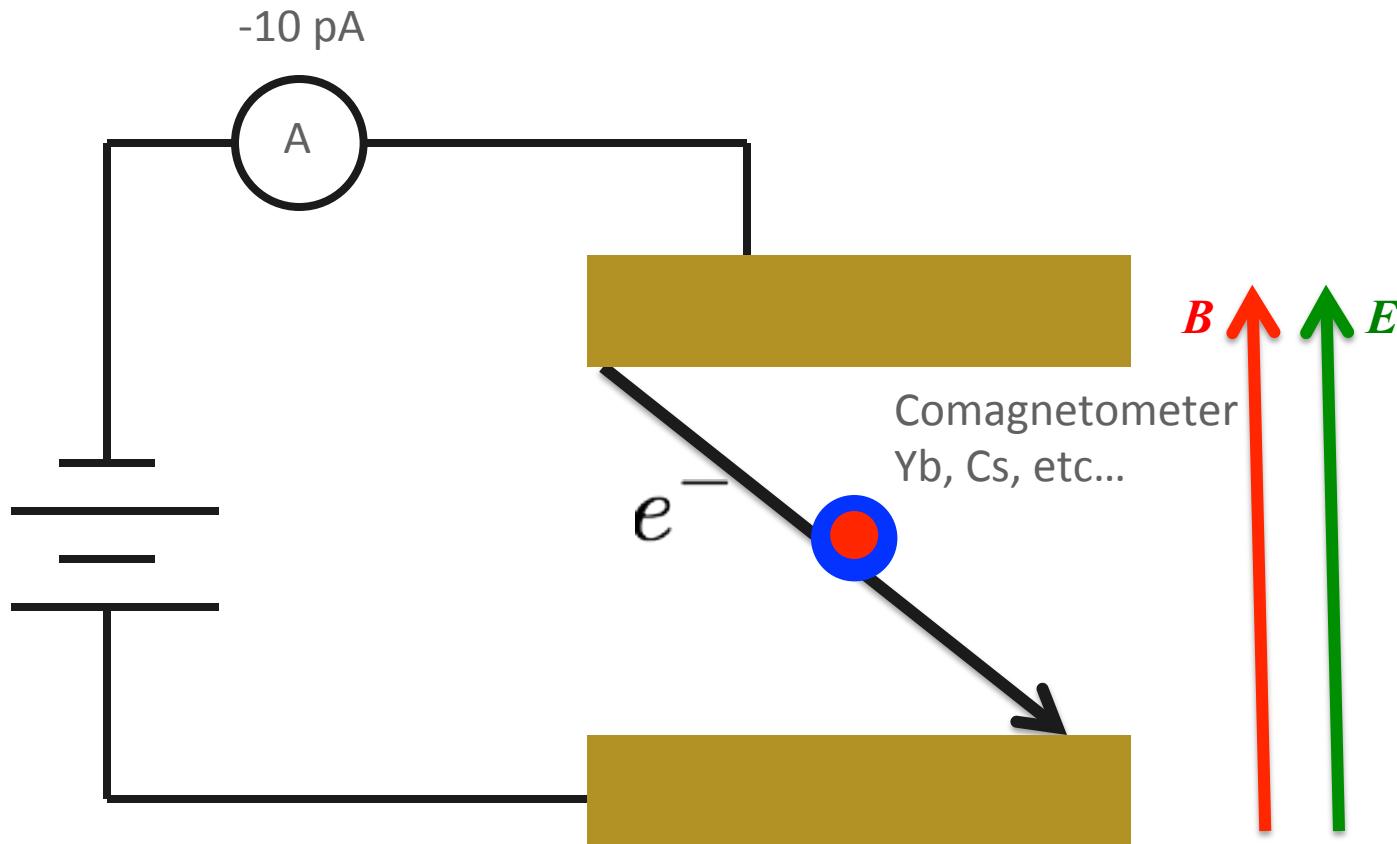


Leakage Current Systematic

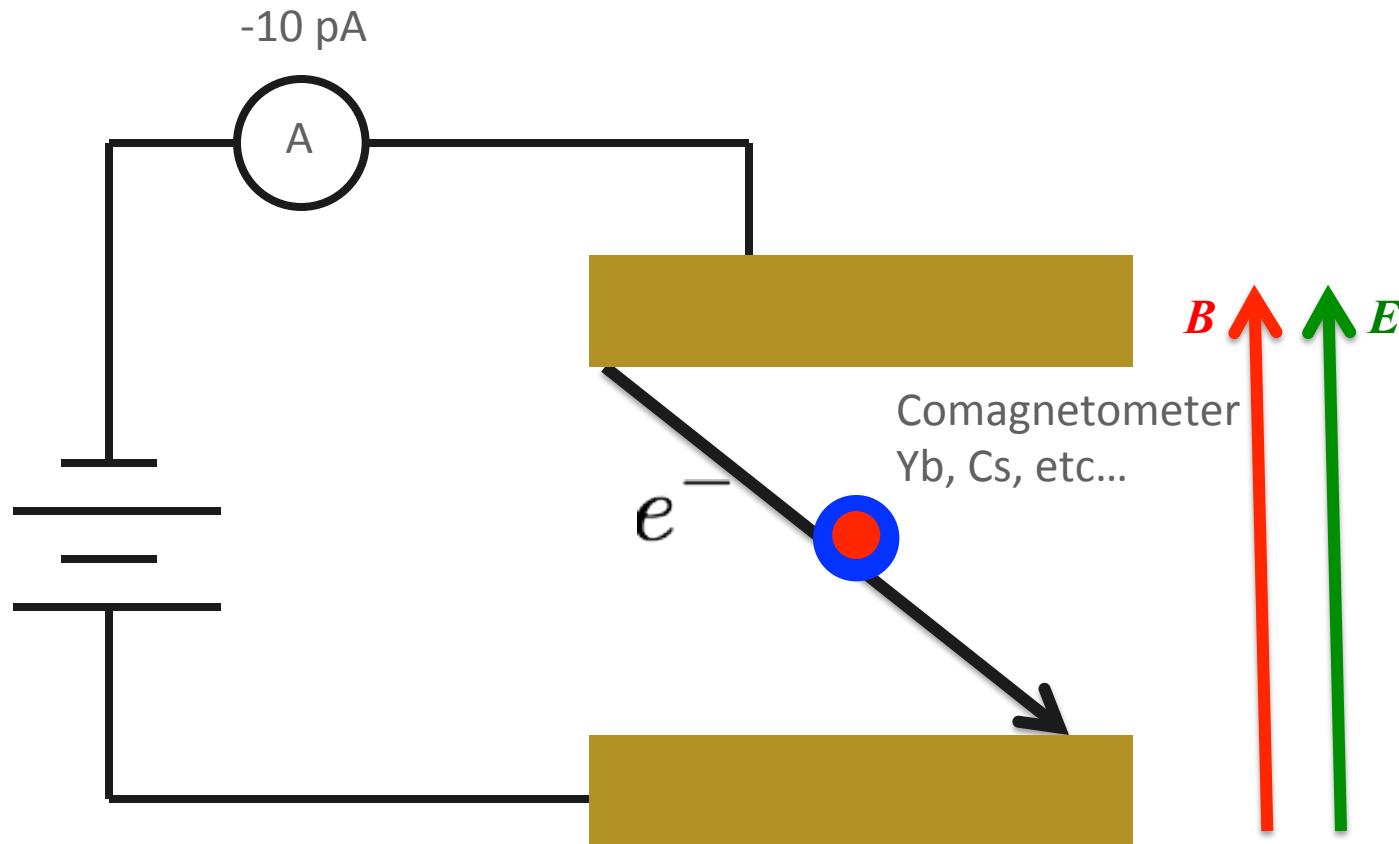


Appears as EDM Mimicking Systematic

Leakage Current Systematic



Leakage Current Systematic



Comagnetometer dramatically improves upper limit on systematic size

Projections

	Phase I	Phase II	Project X
Statistical (e cm)	3×10^{-26}	10^{-27}	10^{-28} to 10^{-29}
Systematic	Phase I (e cm)	Phase II w/ Comagnetometer (e cm)	
Leakage Current (10 pA)	3×10^{-26}	5×10^{-30}	
Stark Interference	5×10^{-27}	5×10^{-30}	
Exv Effects	$< 2 \times 10^{-27}$	5×10^{-30}	
Geometric Phase	10^{-35}	10^{-35}	

A picture says at least two words...



EDM Sectors

Strong CP Problem:

- * CP -violation can be easily incorporated into QCD Lagrangian
- * does not appear to be a feature of the theory – why?

Baryon Asymmetry of the Universe (BAU)

- * CP -violation is one of Sakharov's conditions for dynamically generating BAU
- * CP -violation within the CKM matrix is not enough to explain the observed BAU

